3D Printable Wax-Silicone Actuators

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Abstract:
The Solid Freeform Fabrication of actuators has been an area of active development. So far only weak polymer actuators, or small displacement piezoelectric, and pneumatic actuators have been produced. We developed a novel material platform of silicone and wax which can be used to make soft actuators that are thermally activated. The material is made by mechanically mixing liquid silicone and liquid paraffin wax and cooled to create a suspension of wax particles suspended in a silicone liquid. The resulting material expands by up to 6% of volume when heated above the wax melting temperature.

Keywords: Wax, Actuator, Robocasting

1. Introduction:

The production of actuate-able materials is an important area of development for Solid Freeform Fabrication (SFF). Traditionally manufactured actuators have a diverse set of power sources and applications. These range from hydraulic and pneumatic systems, used in heavy equipment, to electric motors, to piezoelectric systems used for small scale manipulations. Each actuator type is generally judged upon many performance metrics, and is then selected for the needs of a particular application. For a 3d printed actuator to be deemed useful, it must be able to compete with its similar non-printed actuators.

3D printing of actuators has several potential advantages over traditionally manufactured actuators. 3D printing allows for rapid prototyping, allowing a user to iterate through design very quickly. A 3D printable actuator would allow a user to test a design for a new actuator without the costs associated with setting up tooling for a new traditionally manufactured design. 3D printing also offers added geometric complexity over traditional methods. This added geometric complexity may allow for new efficiencies to be achieved. 3D printing can also allow for many diverse material combinations which may allow for complete systems to be produced on a single device

Solid Freeform Fabrication has had limited success in building actuator systems. Ionic polymer metal composite [IPMC] actuators are generally used in a research context and show promise as artificial muscles and microfluidic valves. They often need to have high reliability, fast response times, and low creep. Dr. Evan Malone and Dr. Jonathan Rossiter have both developed 3d printed IPMC actuators with limited success. Such actuators tend to be very weak and have short lifecycles, and suffer from many other shortcomings when compared with traditionally manufactured IMPCs. (Malone and Lipson 2005) (Rossiter, Walters and Stoimenov 2009)

Attempts to produce complete electromechanical motors using electrostatics and electromagnetic designs have relied on printing the plastic components to a system and manually adding wires and conductors. (hakins 2014) (3Ders.org 2014). These are the best efforts today and should not be considered a true 3D printed motor since the vast majority of the complexity and materials in their designs are still produced by hand. However they have allowed people to rapidly prototype a design which could be later optimized for manufacture.

The most successful electrically powered 3d printed actuators are human muscle cells. While these have no industrial counterpart, they have been integrated into 3D printed constructs to make systems which respond to electrical stimuli. (Cketkovic 2014) Such designs may use added geometric complexity enabled through 3d printing to help the cells receive nutrients in the device while operating.

There have been two successful types of 3d printed actuators, piezoelectric and pneumatic. Piezoelectric materials are often used for their high speed movements, small displacements and accurate displacements. These materials have been successfully fabricated using SFF techniques through both direct and indirect methods. (Safari, Allahverdi and Akdogan 2006) 3D printed pneumatics have been produced using SLS systems by Festo and integrated into other complex assemblies. (Festo AG & Co. KG 2013) These actuators have had a high level of reliability and durability. The ability to 3d print pneumatic actuators allows for the integration of many support components (fluid lines, mounting brackets, etc.) to be integrated into a single printed part. Festo's work and the work on piezoelectric materials has brought the advantages of rapid prototyping to the development of these actuators.

Wax actuators are used in a limited set of applications. In general they are used for high reliability short stroke and high power density applications. Often they are used as part of a temperature regulation system in greenhouses, appliances, HVAC and automotive applications. The system can rely on ambient heat or heat generated by electrical resistance to actuate. A wax actuator traditionally uses a single chamber of wax in a metal enclosure which is attached to a membrane or piston. When the wax melts, it expands causing the piston to move or the membrane to inflate. (Thermomegatech 2014) (Tibbitts 1991) Cooling the wax causes it to contract and return to the original configuration. The melt profile of the wax can be customized to allow for sharp transitions at specific temperatures, or spread out over a range of temperature to allow for positional control between its contracted and expanded state. Solid freeform fabrication has been printing with wax materials for many years. (Solidscape 2014) (Cohen and Lipson 2010) However wax has not been combined with other materials to make a printed wax actuator until this paper.

2. Wax actuator Fabrication methods and results:

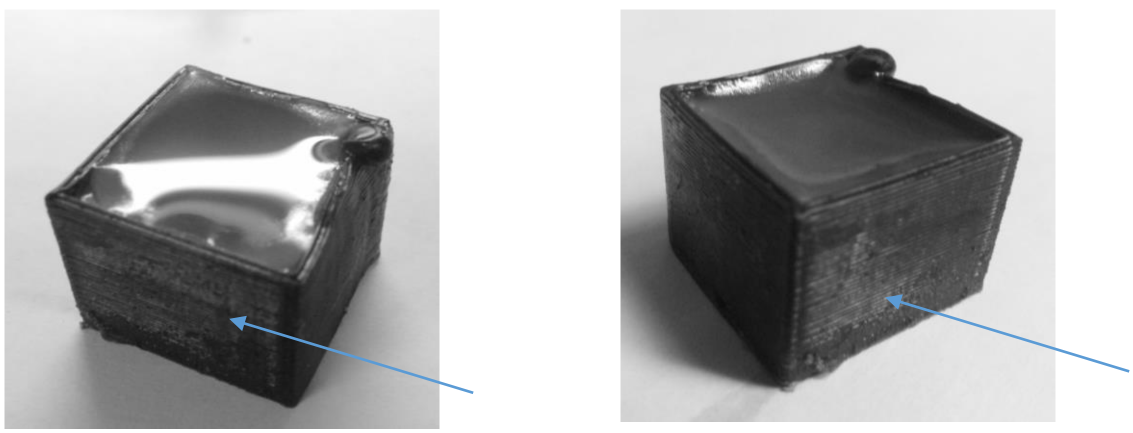
2.1 Emulation

Our early attempts to produce a wax actuator were focused on replicating the design of traditionally manufactured wax actuators. A chamber of ABS was made, and solid wax was placed in the chamber and the top was sealed with silicone. The ABS chamber had been tested for water tightness to assure there were no errors in the print process. When heated the liquid wax would seep out through ABS part and run down the sides. This is most likely due wax having a much lower surface tension than water. This allows the wax to move through very small holes and cracks in the casing. Attempts were made at coating the ABS parts in silicone to prevent leaking, however this failed to produce a design which would noticeable expand when heated.

2.2 Direct Fabrication with dual printing

The second attempt at 3d printing a wax actuator focused on the production of cells of Dow Corning 732 RTV silicone filled with Wax. These were printed on a Fab@Home 3d printer using a pressure based extruder. The top of the cells were left open to produce a structure that was open on the top and sealed on 5 sides. Liquid wax was then filled into the RTV silicone cavity using the robotcasting process, and allowed to sit until the wax cooled and became solid. Silicone was added on top of the cooled cells and allowed to cure.

This method resulted in a two problems (See figure 1). The wax contracts when cooled causing the top of the system to concave inwards. As a result, the top surface could not be properly sealed since the top surface was not at the proper height. The initial solution was to add additional wax to the cooled wax to fill the voids. The second problem was caused by the low surface tension in the wax. The liquid wax would often coat the top surface of the silicone walls. Since the silicone and wax do not bond, the layers printed on top of these walls would not be able to bond to the wall. Thus when the wax was heated, it would leak from the top of the silicone walls and flow down the sides of the silicone cells.



(a) (b)

Figure 1: a cell filled with liquid wax (a) develops a depression (b) as it starts to cool. Overfilling errors and spills can cause wax films to form on the silicone surfaces as seen in the areas highlighted with the blue arrows

The solution to both problems was to use the print itself as a mold (see Figure 2). The cells would be printed on a Fab@Home Model 3 system and allowed to cure overnight. The mold would then be filled with liquid wax and allowed to cool. Wax would be added after cooling to fill in the depressions left in the center of the cells, and allowed to cool. A blade would then cut off excess wax from the top of the cells. The wax was removed from the cells and set aside. The open and empty cells were then removed from the printer and washed in a bath of water at 85 degrees Celsius for five minutes. This caused the wax which had coated the silicone walls to melt and float to the surface. Manual probing was conducted on the cells to determine that wax had been removed. The cells were then removed from the bath and placed back on the printer. The wax was then placed back into the cells and the top layer of the cells was then printed and allowed to cure overnight.

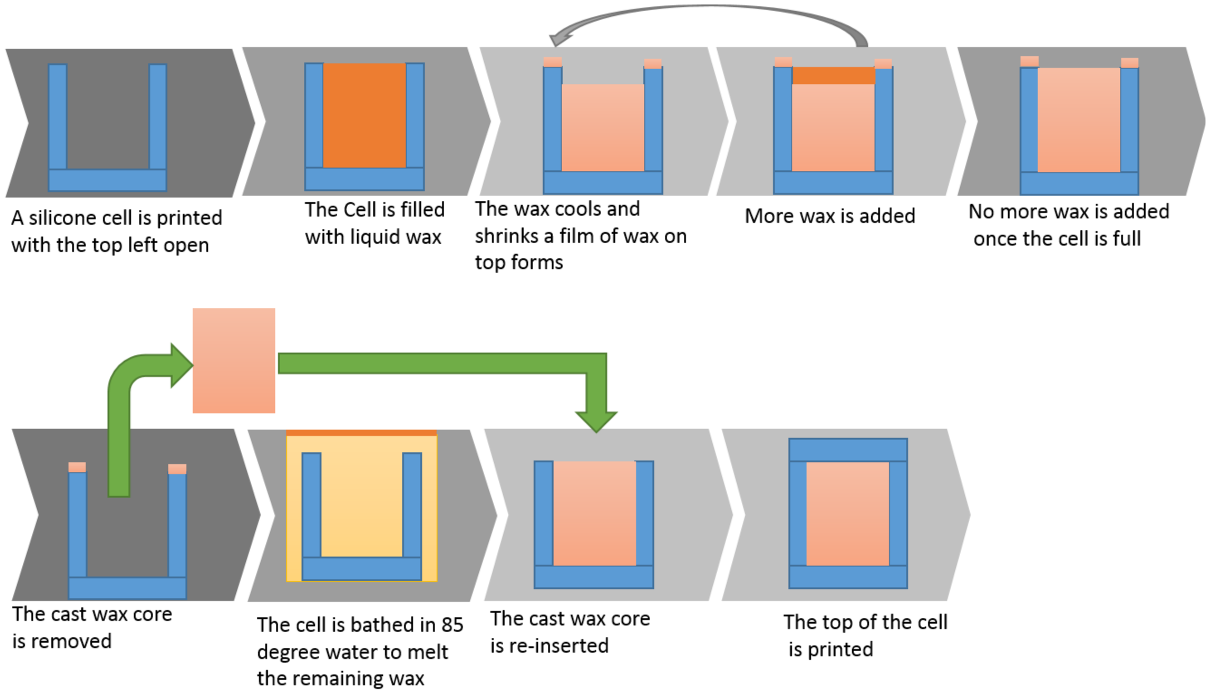
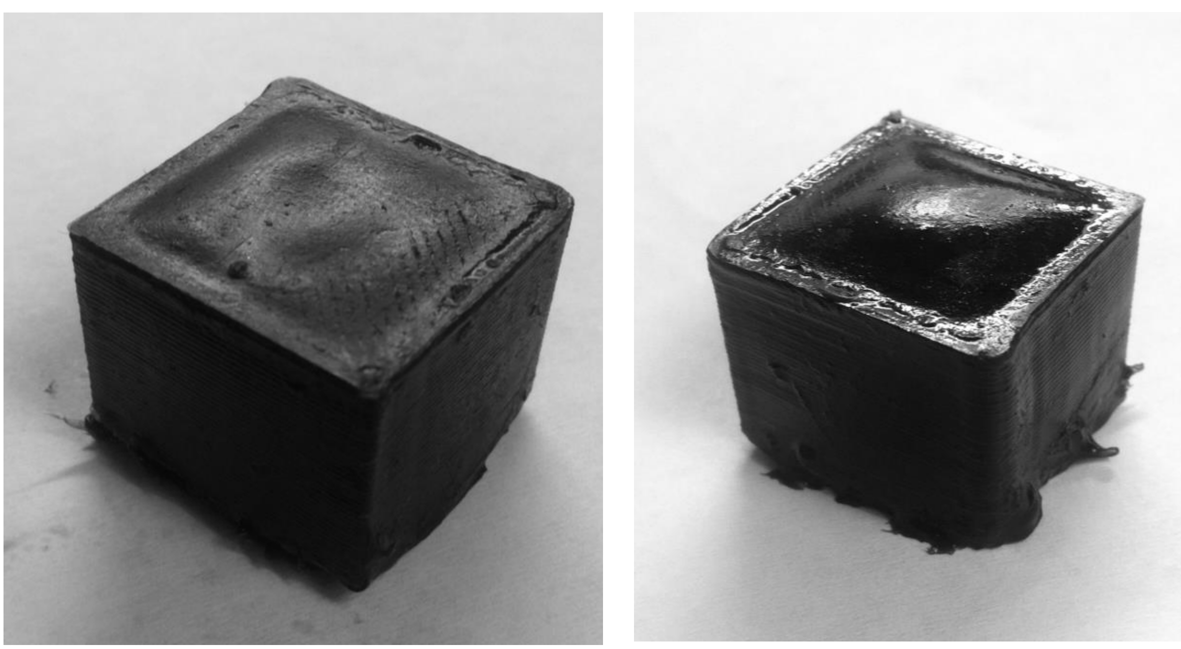


Figure 2: The method for producing wax actuators with Solid Freeform Fabrication and casting contains nine steps. The wax is poured into the printed cell which acts as the mold for the first 5 steps. The cell is cleaned in steps 5 through 8 and finished in step 9.



a B

Figure 3: a sealed cell after 1 cycle of heating (a) can be reheated, causing expansion in the cell. (b) the cell will find the lowest energy state for the new internal volume. A thin side can direct the expansion into that a direction (b)

Closed wax filled cells produced using this method were then measured in the X, and Y directions at their thickest points. They were then put in a bath of water at 85 degrees and left until no solid wax could be felt by manual probing. They were then measured at their thickest point and the change in dimensions were recorded. Cells produced using this method exhibited a 5% to 9% increase dimensional length as a result of heating (see Figure 3).

2.3 Novel Material formulation

As an alternative to the method described above, a new material combination was developed. A mixture of a two part Polydimethylsiloxane (PDMS) of Ecoflex 0050 by Smooth-On and wax was used. The mixture produced a suspension of small wax particles inside of a PDMS Matrix. The material could be extruded from a Fab@Home Model 3 System using an 18 gauge tapered plastic tip from Nordson EFD on the Fab@Home system (see figure 4). Smaller tips resulted in jams due to the small beads of wax suspended in the PDMS. The size of the beads and distribution of sizes has not yet been determined. The PDMS was selected for its higher elongation at break, lower shore hardness Dow Corning 732 Silicone. Additionally RTV silicone proved unable to easily mix with wax due to its one part acetoxy cure process. The heat from the liquid wax caused the RTV silicone to cure too quickly when mixed and caused the wax to form large chunks, resulting in a material not compatible with robocasting on a Fab@Home system

To produce the material, the PDMS was mixed together at room temperature, following the procedure described by Smoot-on. After the ecoflex was mixed, it was placed in an open metal container and liquid paraffin wax was gently added to the metal container so as to prevent material from leaving the container. The PDMS and liquid wax were then mechanically mixed rapidly. The wax cooled as a result of the thermal energy transfer from the wax to the PDMS. The wax was not allowed to pool or stagnate in the container as the entire volume of PDMS and wax was mixed. Mixing was stopped once the entirety of the wax had cooled to room temperature. The mixture of wax and PDMS was then optionally placed in a vacuum chamber to degas the mixture. The PDMS compound has a pot-life of 18 minutes, cures in 3 hours, and must cure at temperatures above 18 degrees Celsius according to Smooth-On. To comply with these requirements, a material batch must be prepared and used rapidly to ensure quality. After printing the parts must be allowed to sit to fully cure.

In order to characterize the effects of the wax to PDMS concentration, several different ratios of wax to PDMS by liquid volume were produced and tested. In order to test the thermal expansion of the material, molds were out of ABS on an FDM system. The molds were 10 mm wide, 10 mm tall, and 45 mm long. The PDMS-wax mixture was placed in the mold and allowed to cure. The molded PDMS-wax mixture was removed once cured and placed in a bath of water at 85 degrees Celsius, above the melting temperature of the wax. Once all of the wax was melted (as determined through manual probing), it was removed from the liquid and measured in the longest direction using calipers with an accuracy of 0.01mm.

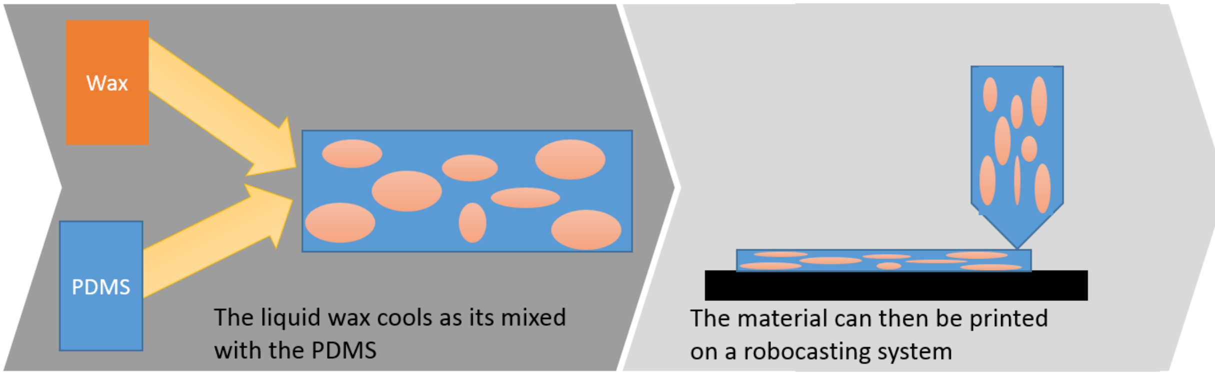
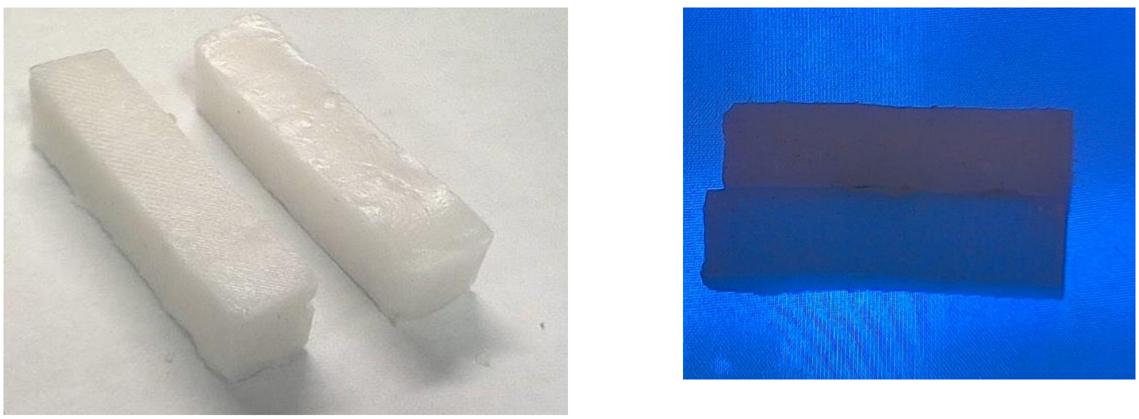


Figure 4: The liquid wax (bright orange) is mixed with the PDMS mechanically and rapidly. While mixing the wax solidifies. The PDMS-wax material must be printed quickly before for PDMS pot-life ends and the viscosity begins to change.



(a) (b)

Figure 5: The PDMS is clear, but the solid PDMS-wax material takes on a white color.(a) The material becomes translucent to visible light when the wax melts.(b)

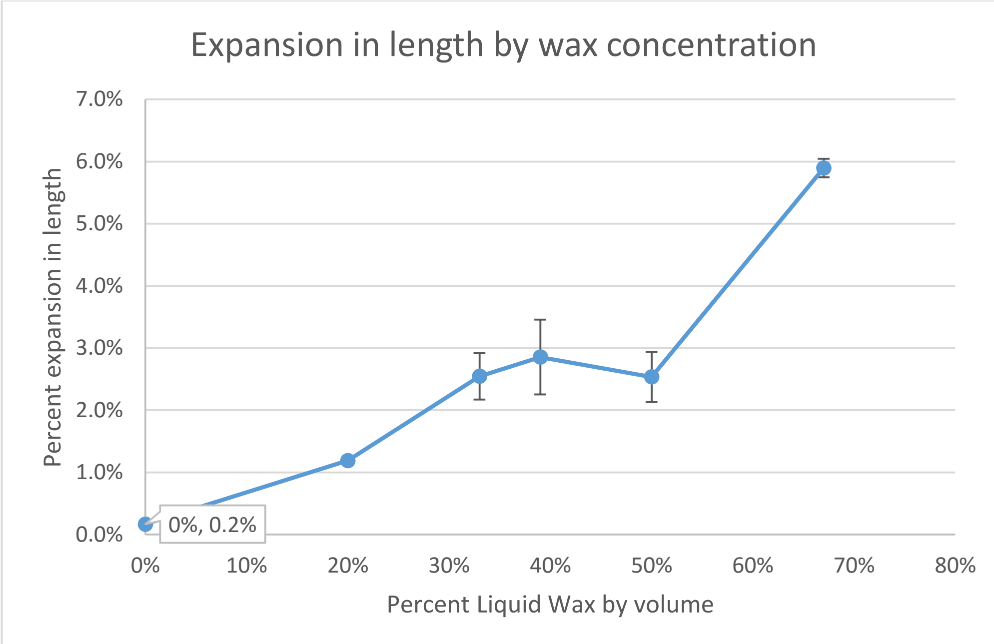


Figure 6: Increasing the percentage wax in the material increases the amount the material expands when heated. There is an unexpected decrease in the percentage of expansion between 40% and 50% of wax by volume. The cause of this decrease is unknown.

Concentrations of 0%, 20%, 33% 39% 50% and 66% by liquid wax of the material were made and tested. As shown in Figure 6 the material showed a definite increase in length relative to the pure PDMS sample. Since PDMS has a relatively high coefficient of thermal expansion of $3.10*10^{-4}\ \frac{mm}{mm}\frac{1}{K}$ it is expected that the PDMS will increase in size when heated from room temperature to 85 degrees Celsius. Since the ambient temperature was not recorded, it is not possible to compare the results with the value expected in literature accurately. However, an estimate of 21 Celsius for room temperature would give a 0.19% increase in length when heated to 85 degrees Celsius and a 0.2% increase in length was measured. The trend in the data of figure 6, shows that as the concentration of wax is increased, the material expands more. There is a deviation in this trend at the 50% concentration and the cause of this deviation is unknown.

3. Discussion and future work:

Two methods for producing a wax actuator using Solid Freeform Fabrication have been demonstrated. Both the PDMS-wax and silicone cell actuators have several advantages over traditional wax actuators. Both systems are complexly soft, allowing them to be integrated into the growing field of soft robotics. Both system are completely metal free, allowing them to operate in environments like MRIs, where traditional wax actuators would be unable to operate due to their metal housings and pistons. Both systems are volumetrically expanding by nature. This may provide the ideal actuator for systems as described in the evolutionary biology work of Jeff Clune and Nick Cheney. (Cheney, et al. 2013)

The direct fabrication method is very time intensive and requires a multistep process for producing a functional wax actuator. The main time constraint on the process, is the curing of the RTV silicone. It has two steps of curing, each requiring 24 hours to ensure a complete bond. Future version of the process should be able to avoid this requirement by using a UV cure silicone or a silicone with a faster cure time. The need for multiple filling steps, a heated bath, and two manual steps make it an inferior process to printing with the novel PDMS-wax material.

The PDMS-Wax mixture's main drawback is the short shelf-life. Using a silicone with a longer pot-life would allow for the usage of the PDMS-wax material to be easier, but would only help by moving the shelf life from minutes to hours. Such longer pot-life materials generally also have a longer curing time, which will only slow down the process of producing wax actuators. Using a UV cured silicone should also allow for an increased shelf life on the order of months or years. Future experiments will have to be done to find a compatible UV silicone material. As seen in figure 5, the PDMS-wax material is milky white when cool and solid but becomes translucent when heated and expanded. This may provide a method of sensing for controlling the actuator in the future.

4. Conclusion

In this paper we have demonstrated the first 3D printed wax actuators. We have developed two methods, a direct fabrication method and a novel material for 3d fabrication. The direct fabrication method is a multi-step process which requires manual steps to produce a 3D printable wax actuator. The novel material we have developed allows for the direct extrusion of a material which will expand when exposed to ambient temperature above the wax melting point. The methods open up a set of applications for 3d printing in the space of passive thermal management and active thermal actuation.

5. Acknowledgements

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6. Bibliography:

3Ders.org. 2014. *An 3D printed electrostatic motor with high torque.* 7 14. http://www.3ders.org/articles/20131226-free-energy-an-3d-printed-electrostatic-motor-with-high-torque.html.

Cheney, N, R MacCurdy, J Clune, and H Lipson. 2013. "Unshackling Evolution: Evolving Soft Robots with Multiple Materials and a Powerful Generative Encoding." *Proceedings of the Genetic and Evolutionary Compuation Conference.*

Cketkovic, C. et Al. 2014. "Three-dimensionally printed biological machines." *Proccedings of the National Academy of Sciences.*

Cohen, D L, and H Lipson. 2010. "Geometric feedback control of discrete-deposition SFF systems." *Rapid Prototyping Journal* Vol. 16, No. 5, pp. 377-393.

Festo AG & Co. KG. 2013. *Learning Gripper.* Esslingen: Festo.

hakins, Christopher. 2014. *Homemade 3d Printed Stepper Motor.* 7 1. https://www.youtube.com/watch?feature=player_embedded&v=paT63-8DLbs.

Malone, Evan, and Hod Lipson. 2005. "Freeform Fabrication of Ionomeric Polymer-Metal Composite." *Solid Freeform Fabrication Symposium.* Austin Texas.

Rossiter, Jonathan, Peter Walters, and Boyoko Stoimenov. 2009. "Printing 3D dielectric elastomer actuators for soft robotics." *Electroactive Polymer Actuators and Devices.* The International Society for Optical Engineering. Volume 7287.

Safari, A, M Allahverdi, and K Akdogan. 2006. "Solid freeform fabrication of piezoelectric sensors." *Journal of Materials Science* 117-198.

Solidscape. 2014. *3D printers.* 7 12. http://www.solid-scape.com/products/3d-wax-printers-rapid-prototyping-services-dimension-3d-printers.

Thermomegatech. 2014. *Compact Button Cell actuator.* 7 1. http://www.thermomegatech.com/products/Compact-Button-Cell-Actuator-%28Sample%29.html.

Tibbitts, Scott. 1991. "Highoutput paraffin linear motors: utilization in adaptive systems." *Active and Adaptive Optical Components* 389-399.